Beyond Lithium: A New Era of Sustainable Energy Engineering

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Since first commercialized by SONY in 1991, Lithium-ion batteries (LIBs) have played a vital role in the translational development of portable electronics and the electrification of transportation, which has re-shaped our life dramatically. However, there is an increasing concern regarding the resilience of supplying raw ingredients in LIBs production, including the unevenly distribution of lithium in the world (~40% in South America) and naturally insufficient in the Earth's crust (0.0017 wt%), the unethically sourcing of Co in the Democratic Republic of Congo, as well as the eccentric availability of graphite in only a few regions globally, predominantly in China. These concerns are further corroborated by the slow implementation of recycling strategies at a relevant industrial scale. Although the 'conventional' LIBs will likely continue to play a critical role in our sustainability roadmap towards Net Zero emission, it is highly desirable to explore future sustainable battery technologies to diversify the battery market to satisfy a variety of demands in energy storage and mobility as well as to ease the dependency on the critical materials.

Guided by above vision, the Special Issue of '*Beyond Lithium: A New Era of Sustainable Energy Engineering*' scopes the interdisciplinary research towards novel electrochemical energy conversion and storage technologies, with the aim to enable further fundamental understanding of disruptive structure-property relationships in new battery chemistries along with novel and battery recycle strategies for future. Apart from scanning the curriculum development, this editorial particularly highlights technical remits from the realization of frontier electrochemical energy storage system (i.e. metal and metal ion battery technologies (Na, K, Ca-, Al, Zn, etc), solid state batteries, dual/multiple ion batteries, flow batteries, etc) and battery recycling strategies (circular economy).

1. *The frontier electrochemical energy storage system*. Lithium Oxygen/air (Li-O/Li-Air) batteries, Lithium sulphur (Li-S) and Lithium Selenium (Li-Se) batteries are a group of redox batteries sharing the advantages of ultra-high capacity, long cycling life, environmentally friendly and low-cost due to S and/or Se cathode materials are used. But their intrinsic limitations such as low conductivity and S/Se shuttle effect etc, have been the major hurdles in this research field. Earth abundant elements to act as cation as a replacement to lithium has been discovered, including sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), zinc (Zn) and aluminium (Al) etc., where most of these battery systems are under early-stage development at a relatively low Technical Readiness Level (TRL). Every component within those batteries is under discovery for performance improvement to a level with potential to replace LIBs, for instance, Sodium-ion batteries (SIB) and potassium-ion batteries (KIB), have been recently identified as emerging technologies to supplement, or even replace LIBs, especially in the applications of large-scale energy storage, with hugely reduced cost and relatively competitive cycling performance and capacity retention thanks from the Na and K metals' similar properties to Li. The electrolyte and its additives for aqueous zinc ion batteries (ZIBs) have been reviewed in this collection to provide future directions and insights for ZIBs' commercialization. Novel energy conversion and storage approaches are helpful add-on, such as thin film energy harvesting systems, liquid metal based energy systems, etc, to diversify the energy supply/distribution as per the regional needs. The above approaches are all promising in the development of frontier electrochemical energy storage system.

2. Battery recycling strategies and circular economy approach. While new discoveries and breakthroughs in battery technologies heavily underpin the areas of energy storage

technologies (high energy density and cycling performance), low-cost and sustainability, a circular economy approach enables an effective recycling strategy for Li-ion batteries as well as a promising alternative to extend the life cycle. Research in emerging battery technologies is a multi-faceted subject, therefore, a special issue in this area is timely and will encompass significant advances made in this crucially important research field. It is reported that a very small portion of batteries are currently being recycled worldwide, with some claims as low as 5%, it is imperative that we look at ways to increase this number through a combination of increasing the ease, speed and profitability of the process. There are many areas of battery recycling that are of great importance, now more than every as the amount of battery increases, currently it is estimated that 80% of a battery can be recycled, but very limited successful cases in Li battery recycling have been proven economically friendly. The road towards a sustainable Li-battery life cycle remains yet to be achieved.

Finally, we anticipate this collection of papers to encompass the research of frontier energy materials to effectively address the challenge toward the Net Zero. We gratefully appreciate the support from the whole editorial team of Small and the reviewers. We would also like to take this opportunity to thank all authors who contributed to this collection.

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